Determinants of task order in dual-task situations

DISSERTATION

zur Erlangung des akademischen Grades doctor rerum naturalium

(Dr. rer. nat.) im Fach Psychologie

eingereicht an der Mathematisch-Naturwissenschaftlichen Fakultät II

der Humboldt Universität zu Berlin

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Tag der Verteidigung: 2. Dezember 2014

Abstract

The simultaneous performance of two tasks in a dual-task paradigm is often accompanied by dual-task costs, i.e., longer reaction times and/or higher error rates. These dual-task costs have been explained by the existence of a central bottleneck which prohibits the simultaneous processing of the two tasks at the central response-selection stage of information processing. What has not been sufficiently investigated so far is which factors determine the task processing order at the central bottleneck. The aim of the present work was to investigate several of the possible factors which determine the task order by using a dual-task paradigm of the psychological refractory period (PRP)-type with random task order. In my experiments, I could show that the arrival time of the two tasks at the bottleneck plays a role in the determination of task order. Additionally, I could show that the influence of the arrival time on processing order is independent of the component task which is manipulated to test the influence of that task (i.e., visual & auditory task). In addition, I could show that the instruction is a determinant of task order and relate this finding to cognitive control processes which seem to be activated under certain instruction conditions. As a third factor, I investigated task requirements by comparing a temporal order judgement task with a dual task with random task order, i.e., temporal order judgement with the additional requirement to do a choice-RT task. The results of my experiments additionally suggest that the decision about the temporal order of the two tasks seems to be located between the perception stage and the response-selection stage of processing.

Keywords: dual tasks, task order, arrival time, task requirements

Zusammenfassung

Werden zwei Aufgaben in einem Doppelaufgaben-Paradigma gleichzeitig bearbeitet, dann treten oft sogenannte Doppelaufgabenkosten auf, d.h.: längere Reaktionszeiten und/oder höhere Fehlerzahlen. Diese Doppelaufgabenkosten werden durch einen zentralen "Flaschenhals" erklärt, der die gleichzeitige Verarbeitung der beiden Aufgaben an der zentralen Verarbeitungsstufe der Reaktionsauswahl verhindert. Was bisher noch nicht ausreichend untersucht wurde, ist, welche Faktoren die Verarbeitungsreihenfolge an diesem zentralen Flaschenhals bestimmen. Das Ziel der vorliegenden Arbeit war es, einige mögliche Faktoren mit Hilfe eines Doppelaufgaben-Paradigmas vom Typ der Psychologischen Refraktärzeit mit zufälliger Aufgabenreihenfolge zu untersuchen. In meinen Experimenten konnte ich zeigen, dass die Ankunftszeit am Flaschenhals die Verarbeitungsreihenfolge beeinflusst. Zusätzlich konnte ich zeigen, dass der Einfluss der Ankunftszeit auf die Verarbeitungsreihenfolge unabhängig davon ist, welche der beiden Aufgaben manipuliert wurde um den Einfluss dieser Aufgabe zu untersuchen (visuelle oder auditorische Aufgabe). Außerdem konnte ich zeigen, dass die Instruktion ein bestimmender Faktor der Verarbeitungsreihenfolge ist und dieses Ergebnis in Bezug bringen zu kognitiven Kontrollprozessen, die bei bestimmten Instruktionsbedingungen aktiviert zu werden scheinen. Als dritten Faktor untersuchte ich Aufgabenanforderungen, indem ich eine Aufgabe mit zeitlicher Reihenfolge-Entscheidung mit einer Doppelaufgabe mit zufälliger Aufgabenreihenfolge, d.h.: Bestimmung der zeitlichen Reihenfolge mit der zusätzlichen Anforderung einer Reaktionswahl-Aufgabe, verglich. Die Ergebnisse meiner Experimente deuten zusätzlich darauf hin, dass die Entscheidung über die zeitliche Reihenfolge der beiden Aufgaben zwischen der Wahrnehmungsstufe und der Reaktionswahlstufe getroffen wird.

Schlagwörter: Doppelaufgaben, Aufgabenreihenfolge, Ankunftszeit, Aufgabenanforderungen

Acknowledgments

Auf dem Weg zur Fertigstellung dieser Doktorarbeit haben mich viele Menschen begleitet und unterstützt. Ihnen möchte ich hier danke sagen:

Zu allererst möchte ich mich bei meinem „Doktorvater“ Torsten Schubert bedanken, der mich in jeder Hinsicht bei der Arbeit an der Dissertation und darüber hinaus unterstützt hat. Dafür ein großes Dankeschön!

Mein Dank gilt auch meinem Kollegen Tilo Strobach, der immer ein offenes Ohr für Fragen hatte und nebenbei neue Rekorde im Korrekturlesen aufgestellt hat.

Hermann Müller möchte ich für die Möglichkeit danken, an seinem Lehrstuhl zu arbeiten.

A big thanks goes to the great friends and colleagues from the Ludwig-Maximilians-University Munich, especially to Emil Ratko-Dehnert, Saurabh Dhawan, Yiquan Shi, Stephanie Ganzenmüller, Dragan Rangelov, Isabel Koch, Giulia Manca, and René Gilster. Thank you for making the time at the LMU a memorable one!

Ich danke auch meinen Eltern, Elisabeth und Franz Müller, die mir diesen Weg durch ihre Unterstützung ermöglicht haben.

Meiner Mutter Elisabeth Müller und Simone Schuster möchte ich für die vielen Stunden danken, die sie auf Pauline aufgepasst haben, damit ich diese Arbeit schreiben konnte.

Mein größter Dank geht an meinen Mann Andreas, der einen riesigen Teil dazu beigetragen hat, dass diese Arbeit fertig wurde: Andreas, du warst bei den Höhen und Tiefen der Promotionszeit immer für mich da, mit ehrlichem Feedback oder mit Aufmunterung. Ich bin sehr dankbar dafür, dass es dich gibt und freue mich total auf die zukünftige gemeinsame Zeit mit dir und unseren Kindern!

Publications Included

Study 1:

Hendrich, E., Strobach, T., Buss, M., Müller, H., & Schubert, T. (2012). Temporal-order judgment of visual and auditory stimuli: Modulations in situations with and without stimulus discrimination. Frontiers in Integrative Neuroscience, 6:63.

Study 2:

Hendrich, E., Strobach, T., Buss, M., Müller, H., & Schubert, T. (under revision). “First come, first served”: Processing order of two tasks is influenced by their arrival times at the bottleneck.

Study 3:

Hendrich, E., Strobach, T., Müller, H., & Schubert, T. (in preparation). Is dual tasks’ “first-come, first-served” principle valid for tasks of different modalities?

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Introduction

When someone does two tasks at the same time, the performance in one or both tasks usually suffers. Almost everyone of us has experienced this phenomenon in daily life. But it has also been the subject of scientific research for years. Dual task studies have been investigating the consequences of doing two experimental tasks simultaneously and where the resulting dual-task costs (longer reaction times [RTs] and/or higher error rates in dual tasks in contrast to single tasks) come from. There have been several theories about why the processing of one task interferes with the processing of another task. According to Pashler (1994), three of the most important explanations are capacity sharing, bottleneck models, and cross talk models. The capacity sharing account assumes that we possess a certain amount of mental resources or processing capacity, which we share among tasks. If we do more than one task, there is less capacity for the individual tasks and the performance suffers (Kahneman, 1973; Navon & Gopher, 1979).

Bottleneck models, in contrast, assume that there is a "bottleneck" during information processing which prohibits the parallel processing of certain mental operations (Pashler, 1994). These operations can only be done for one task at a time, which means that the processing of the other task is delayed at this point in processing, i.e., the bottleneck. The third kind of models which try to explain dual-task interference, are cross-task models (Pashler, 1994). These models assume that the interference is dependent on the kind of information that is processed. The common assumption is that interference results if the two tasks involve similar information, e.g., similar sensory input (Pashler, 1994).

Although the three theories are not mutually exclusive, several studies have found support for a central bottleneck (e.g., McCann & Johnston, 1992; Pashler & Johnston, 1992; Schubert, 1999). These studies apply component tasks that can be divided into three consecutive stages: perception, response-selection, and response execution. In other words, a stimulus is perceived and identified, then an appropriate response to the stimulus is selected, and at last the chosen response is executed. The idea of a central bottleneck assumes that information processing of two tasks can run in parallel at each stage of processing except for the central response-selection stage (see Figure 1, Panel A).

Evidence for the central bottleneck comes from PRP (Psychological Refractory Period) studies. In the PRP paradigm, the participants perform two choice RT tasks which are presented with a short and variable interval (stimulus onset asynchrony [SOA]) between the two stimuli (Schubert, 2008). What is usually found is that the RT to the first task (RT1) is not affected by the SOA, while the RT to the second task (RT2) is increasing with decreasing SOA (Pashler, 1994). In other words, Task 2 performance suffers more if the time between the presentation of the two tasks is shorter, while Task 1 performance is often unaffected. This finding can be easily linked to the idea of a processing bottleneck: if Task 1 processing is claiming the bottleneck first, Task 2 processing has to wait until Task 1 processing is completed. This leads to a delay in Task 2 processing and thus to a longer RT2 (Pashler, 1994; Schubert, 2008).

The studies which investigated dual-task interference and the PRP paradigm have most often used dual tasks with a fixed and therefore predictable task order. Thus, the question is not answered yet how the task order at the bottleneck is determined.

Determinants of task order in dual-task situations investigated in the present work

In the present doctoral thesis, I investigated several aspects of the question of task order in dual-task situations. First, I will describe findings about how the arrival time of the two tasks at the central bottleneck influences processing order (Hendrich et al., submitted). According to the “first-come, first-served” principle, the arrival time of at task at the central bottleneck is a critical factor for the determination of the processing order. In Hendrich et al. (submitted), I could find empirical support for the “first-come, first-served” principle.

The second paragraph is about to which degree the findings which support the arrival time at the bottleneck as determinant of processing order can be generalized (Hendrich et al., in preparation). So far, the influence of the arrival time at the bottleneck has only been investigated by manipulating the visual task in a visual-auditory dual task. I investigated whether the effect of the arrival time at the bottleneck on response order can also be found when the auditory task is manipulated.

The role of the instruction in this context will be discussed in the third paragraph (Hendrich et al., submitted, in preparation). My findings suggest that additional cognitive control processes are activated under certain instruction conditions.

In the fourth paragraph I describe my findings regarding the role of task requirements in determining the task order (Hendrich et al., 2012). Additionally, the findings of this study help to localize the decision time about the task order in the dual-task processing architecture.

Basic dual-task situation

In the studies presented here, I used an auditory-visual dual-task paradigm of the PRP-type. For the auditory task, I presented one of three sine-wave tones with frequencies of 250, 500, and 1000 Hz and a volume of 58 decibel. The tones were presented via headphones. One of three digits was presented as the visual stimulus: “2”, “5”, or “9”. The numbers were presented in white font colour (55 cd/m^2) on dark grey background (0.11 cd/m^2). I used dark grey background instead of black background in order to minimize visual after-effects. A variable SOA (-400 ms, -120 ms, -60 ms, 0 ms, 60 ms, 120 ms, or 400 ms) separated the presentation of the visual and the auditory stimulus. Negative SOAs denote trials in which the number stimulus of the visual task was presented first, while positive SOAs denote trials in which the tone stimulus of the auditory task was presented first. The participants were asked to press the ",", ".", or "-"-key on a QWERT-keyboard for 2, 5, and 9, respectively. For the auditory task, participants responded to the low, middle, and high tone by pressing the "y", "x", or "c"-key, respectively. As a parameter for response order, I measured the percentage of trials in which the auditory task was responded to first ("tone-responded-to-first" trials). Additional dependent measures were RTs and error rates.

1. The "first-come, first-served" principle: Is the arrival time at the central bottleneck a determinant of the processing order?

The first question I investigated, was whether the arrival time at the central bottleneck is a determinant of the processing order of two tasks. The arrival time at the central bottleneck is equivalent to the time at which the perceptual processing of a task is completed. Therefore, it can differ from the presentation time of the stimuli. This is illustrated in Figure 1 (Panel B and C): if the perception stage of the first presented task (Task 1) is prolonged and the perceptual processes of the second presented task (Task 2) therefore are completed earlier than the perceptual processes of Task 1, Task 2 will enter the bottleneck first ("first-come, first-served" principle). Thus, Task 2 will be processed first and this should be reflected in an increase of response reversals, i.e., the participants should respond to Task 2 first. In contrast, a prolongation of the response-selection stage of the first-presented task should not change the order of arrival at the bottleneck of the two tasks and therefore should not have an influence on the response order (see Figure 1C).

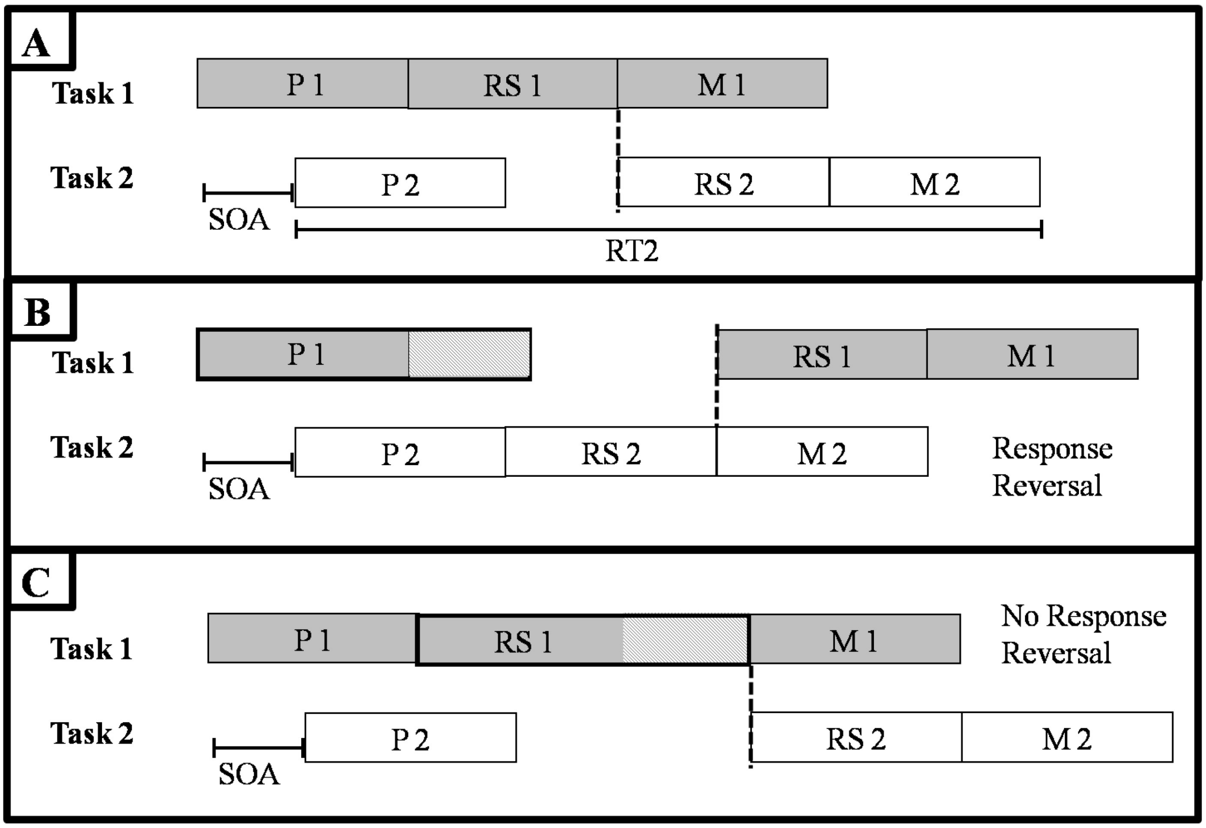

Figure 1. Illustration of the central bottleneck model and the influence of the arrival time at the central bottleneck on response order; P 1 and P 2 = perception stages of Task 1 and Task 2, RS 1 and RS 2 = response-selection stages of Task 1 and Task 2, M 1 and M 2 = stages of motor response of Task 1 and Task 2; Panel A: Illustration of the central bottleneck model. Due to the bottleneck at the central response-selection stage, the processing of Task 2 is postponed until the response selection of Task 1 is completed. Only then can Task 2 processing continue, which leads to an increase of RT2. Panel B: If the perception stage of Task 1 is prolonged and the perception stage of Task 2 therefore completed first, then Task 2 "enters" the bottleneck first and Task 1 processing has to be postponed. This should be reflected by the occurrence of a response reversal, i.e., the response to Task 2 is submitted before the response to the first presented Task 1. Panel C: In contrast, if the response-selection stage of Task 1 is prolonged, this should not lead to a response reversal, as the perception stage of Task 1 is still completed before the perception stage of Task 2 and thus its central processing can occur before the central processing of Task 2.

Recently, there have been some conflicting results to this question. Sigman and Dehaene (2006) found preliminary evidence in favour of the "first-come, first-served" principle. They manipulated the visual task in an auditory-visual dual-task paradigm and presented the two tasks in a random order. The auditory task was to determine whether a tone was high or low in frequency. For the visual task, the participants had to recognize whether a presented number x

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(2011) also used an auditory and a visual task in a dual-task paradigm. The auditory task was to detect whether a tone presented via headphones was heard on the left or right side. For the visual task, the participants had to discriminate between a plus and a minus sign, which was either presented in intact or degraded form. The degradation of the visual stimulus was achieved by overlaying the stimulus with a pattern of randomly distributed squares which converted the colours of fore- and background (white and black, respectively). Leonhard and Ulrich (2011) expected a significant interaction of degradation of the visual stimulus and task order (visual-auditory or auditory-visual) on the percentage of response reversals. In visual-auditory trials, the degradation of the visual stimulus should lead to an increase of response reversals. Contrary to Sigman & Dehaene, Leonhard and Ulrich (2011) used a fixed task order in two of their experiments (visual-auditory) and found no increase in response reversals if the visual perception stage was prolonged.

In the third experiment the task order was random; however, the results were unexpected. The percentage of response reversals for the visual-auditory trials seemed to decrease when the visual stimulus was degraded instead of the expected increase. In other words, when the visual stimulus was degraded, the participants responded more often in the order of task presentation than when it was not degraded. However, the authors have argued that the degradation of the visual stimulus might not have led to a prolongation of the perception stage, but instead might have made it more salient to the participants and thus led to an earlier detection time. This earlier detection time of the visual stimulus could have led to the decrease in response reversals as it made the stimulus order even clearer to the participants.

In view of this contradictory findings, my first aim was to investigate whether the arrival time at the bottleneck plays a role in the determination of the processing order at the central bottleneck. In order to circumvent the methodological issues connected with the above described studies, I chose different kinds of tasks and different kinds of manipulation for the visual task, which were in my view more appropriate to investigate the question. I used a auditory and a visual choice RT task with random task order (as described above) and manipulated the visual task by using a weak stimulus-background contrast (grey font-colour [0.09 cd/m²] on dark-grey background) in order to prolong the perceptual processing of the visual task instead of the "regular" strong-contrast condition (white font colour (55 cd/m²), see paragraph above "Basic dual-task situation"). As the weak contrast led to an increase in reaction time of about 92 ms in a pilot experiment, I expected that the prolongation should lead to an increase in response reversals in trials with negative SOAs (in which the visual task was presented first), at least in trials with the shortest SOA (60 ms) in Experiment 1 (Hendrich et al., submitted, 2012). I prolonged the central response selection stage in Experiment 2 (Hendrich et al., submitted) by manipulating the stimulus-response mapping of the visual task. The mapping was either compatible (numbers in ascending order were mapped to three adjacent keys from left to right) or incompatible (numbers were mapped in a random order to the same three adjacent keys). In case the arrival time at the bottleneck has an influence on processing order, I expected that this manipulation should not lead to an increase in response reversals.

Results & Discussion

In Hendrich et al. (submitted; Experiment 1), I could show that the prolongation of the perceptual processing of the visual task does lead to an increase in response reversals in trials in which the visual task was presented first (see Figure 2, Panel A). This was reflected in a significant interaction of the contrast manipulation and SOA, $F(6, 228) = 3.402$, $p < .01$. Further *t*-tests showed that the proportion of "tone-responded-to-first" trials was significantly higher in the "low-contrast" condition than in "high-contrast" condition for SOA -400 ms, SOA -120 ms, SOA -60 ms, SOA 0 ms, and SOA 60 ms, $ts(39) > 2.185$, $ps < .05$. As explained above, trials with negative SOAs are trials in which the visual task was presented first. This means that the prolongation of the perception stage of the visual task led to an increase in response reversals primarily in trials in which the visual task was presented first.

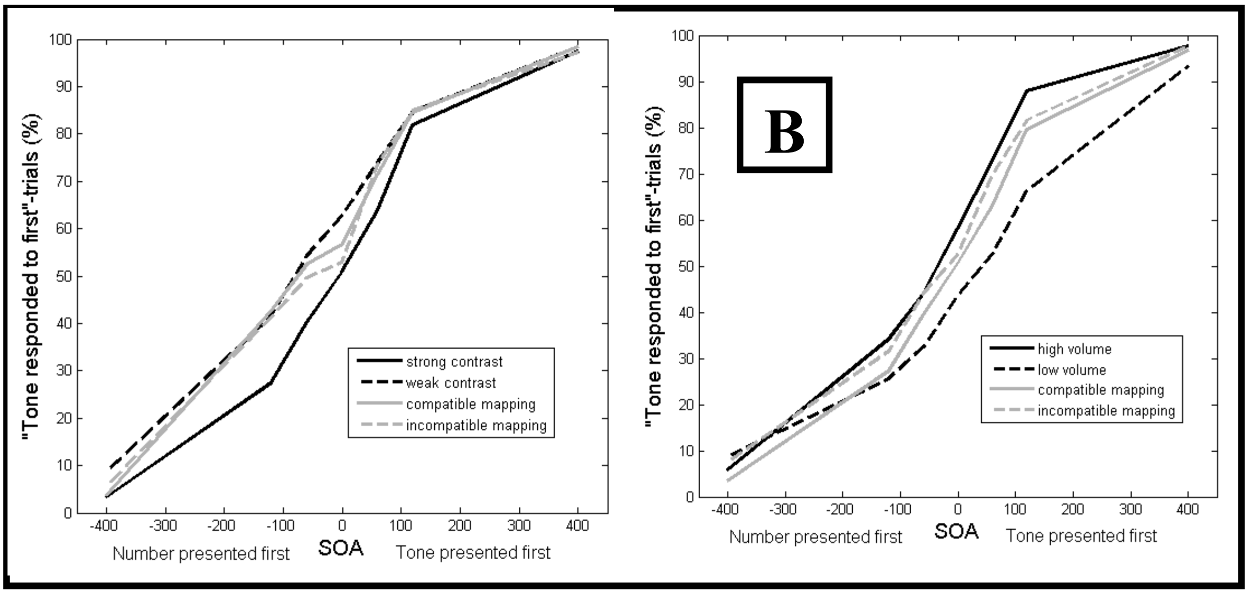

Figure 2. Percentage of trials in which the participants respond to the auditory task first for each SOA. Panel A shows the effects of the manipulation of the perception stage (strong vs. weak contrast) and the response-selection stage (compatible vs. incompatible stimulus-response mapping) of the visual task (Hendrich et al., submitted). The prolongation of the visual perception stage leads to an increase of response reversals in trials in which the visual task was presented first. The prolongation of the response-selection stage has no effect on response order. Panel B shows the effects of the manipulation of the auditory task (Hendrich et al., in preparation). The prolongation of the auditory perception stage leads to an increase of response reversals in trials in which the auditory task is presented first, while the prolongation of the auditory response-selection stage leads to a small increase of trials in which the auditory task was responded to first. The results provide support for the “first-come, first-served” principle.

In contrast, the prolongation of the response-selection stage (Experiment 2) did not have an influence on response order, $F(4.86, 179.82) < 1$ (Greenhouse-Geisser corrected), which is also in line with the predictions made by the “first-come, first-served” principle. The results fit the assumption that the processing order at the bottleneck is influenced by the arrival time at the central bottleneck and thus provide evidence for the validity of the “first-come, first-served” principle.

2. Is the “first-come, first-served” principle also valid for other modalities?

In Hendrich et al. (submitted, Experiment 1), the prolongation of the perception stage of the visual task led to an increase in response reversals, which supports the “first-come, first-served” principle. However, there were some points that made it necessary to investigate whether the manipulation of the auditory task would lead to similar results. First, the number of errors in Hendrich et al. (submitted) was higher for the auditory task than for the visual task. This difference in task difficulty could have led to a prioritization of the auditory task, which could have been especially prominent in trials in which the visual task was presented first. Secondly, the auditory task could have been more alerting than the visual task. Several studies have found that auditory warning signals are more effective than visual ones (Bertelson & Tisseyre, 1969; Davis & Green, 1969; Sanders, 1975; Posner, Nissen, & Klein, 1976). It cannot be ruled out that this led to the observed results in Hendrich et al. (submitted). Therefore, in Hendrich et al. (in preparation), I investigated whether the results found in Hendrich et al. (submitted) are dependent on the manipulation of the visual task and therefore modality-specific, or if the results can be extended to the manipulation of the auditory task as well. This would provide even stronger evidence for the validity of the “first-come, first-served” principle.

For the study, the same tasks were used as in Hendrich et al. (submitted), but the auditory task was manipulated instead of the visual task. The perceptual processing of the auditory task was prolonged by presenting the tones in a low volume (25 decibel as well as increasing volume in the beginning of the tone presentation and decreasing volume at the end of the presentation) and by adding a very low white noise. A pilot study showed that the low-volume condition led to an increase in RT of 121 ms compared to the condition with “high” volume (58 decibel as in the experiments before). I expected that the prolongation of the auditory task should lead to an increase in response reversals in trials in which the auditory task was presented first, if the arrival time at the bottleneck has an influence on the processing order at the central bottleneck (Hendrich et al., in preparation; Experiment 1).

As the prolongation of the RT to the auditory task due to the low-volume condition was very large, I also expected that it would aid the participants with recognizing the order of stimulus presentation and thus increase the number of trials with correct response order for trials with negative SOAs, in which the visual task was presented first. The response-selection stage was prolonged in Experiment 2 (Hendrich et al., in preparation) by manipulating the stimulus-response mapping of the auditory task. The mapping was either compatible (tones with ascending frequencies were mapped to three adjacent keys from left to right) or incompatible (tones were mapped randomly to the same three keys). According to the "first-come, first-served" principle, the manipulation of the response-selection stage should not have an influence on response order.

Results & Discussion

As illustrated in Figure 2, Panel B, the results of Experiment 1 in Hendrich et al. (in preparation) show that the prolongation of the perceptual processing of the auditory task leads to an increase in response reversals in trials in which the auditory task was presented first, which was reflected in a significant interaction of the volume manipulation and SOA, $F(6, 258) = 11.182$, $p < .01$. The proportion of "tone-responded-to-first" trials was lower for every SOA except SOA -400 ms, *t*s < 3.766, *p*s < .01. For trials with positive SOAs, in which the auditory task was presented first, this means that the number of response reversals increased due to the prolongation of the auditory perception stage. For trials with negative SOAs (visual task presented first) this means that the number of response reversals decreased and that the percentage of trials in which the participants responded in the order of task presentation, increased.

In Experiment 2, in which the response selection stage of the auditory task was manipulated, the prolongation of said stage did not lead to an increase in response reversals in trials in which the auditory task was presented first, $F(4.762, 200.023) < 1$ (Greenhouse-Geisser-corrected). This means that the results of Hendrich et al. (submitted), who showed that the arrival time at the bottleneck is a determinant of the processing order at said bottleneck, are not only valid if the visual task is manipulated, but also if the auditory task is manipulated (Hendrich et al., in preparation). In summary, the results of the above described studies support the idea that the arrival time at the bottleneck is a determinant for the processing order of two tasks.

But it is not the only determinant, as some further results of the studies show. In Experiment 2 (Hendrich et al., in preparation), the prolongation of the response selection stage of the auditory task led to a small, but significant increase in trials in which the participants responded to the auditory task first across all SOAs, $F(1, 42) = 6.166$, $p < .05$. This small but significant increase hints at the difficulty of the manipulation that was used. The stimulus-response mapping of the auditory task was either compatible (three tones of ascending frequencies were mapped to three contiguous keys from left to right) or incompatible (tones were randomly mapped to the keys).

A possible explanation for this result is that the auditory task, which was more difficult than the visual task in the first place (see higher error rates, Hendrich et al., submitted), put even higher demands on the participants in the incompatible mapping condition. They had to identify the correct frequency of the tone, recognize the stimulus order and, which was perhaps the most difficult task, they had to keep the random mapping in memory. Therefore, they had to increase their effort to maintain task performance which might have led to them responding to the auditory task first more often than in the compatible mapping condition.

Another factor that plays a role in determining the processing order will be described in the next section: the instruction which is given to the participants.

3. The role of the instruction and its connection to cognitive control processes

A further possible determinant of the processing order in dual-task trials with random task order was investigated in Hendrich et al. (submitted) and Hendrich et al. (in preparation): the instruction given to the participants. All experiments were conducted with two different instruction conditions: in the condition with "order" instruction, the participants were told to respond in the order of the stimulus presentation, while the participants in the "free-choice" condition could respond in the order of their choice. Still, it was pointed out that they should respond quickly, accurately, and not systematically, e.g., always to one stimulus first. By manipulating the instruction, I aimed to investigate the role of cognitive control processes in the decision of task order and the realisation of the order processing. While the "first-come, first-served" principle leads to straightforward predictions about the processing order at the central bottleneck, more complex models suggest additional cognitive control processes (e.g., Sigman & Dehaene, 2006; Szameitat et al., 2006). For the experiments in Hendrich et al. (submitted, in preparation), this could mean the following: in the condition with "order" instruction, additional control processes might cause longer RTs than in the condition with "free-choice" instruction (Umiltà, 1988). Also, the activation of these control processes might lead to less response reversals in the condition with "order" instruction than in the "free-choice" instruction.

Interestingly, previous studies on the arrival time at the bottleneck applied varying modes of instructions. In Sigman and Dehaene (2006), the participants were told to respond "accurately and as fast as possible to each [stimulus] as it arrived" (*p*. 1236). In contrast, the participants in Leonhard and Ulrich (2011), who found no evidence in favour of the "first-come, first-served" principle, received no instruction regarding the response order.

Results & Discussion

The data of the experiments in Hendrich et al. (submitted) and Hendrich et al. (in preparation) showed that the manipulation of the instruction does not change the effect of the manipulation of the arrival time at the bottleneck (see Figure 3, Panel A, for an illustration of the results of Hendrich et al., submitted). Neither in the experiment with prolongation of the perception stage of the visual task (Hendrich et al., submitted), nor in the experiment with prolongation of the auditory perception stage (Hendrich et al., in preparation) a significant interaction of stage manipulation, SOA, and instruction could be found: $F(6, 228) = 1.141$, $p = .34$, and $F(6, 258) = 1.584$, $p = .15$. In other words, independent of the instruction that was used the arrival time at the bottleneck had an influence on the processing order of the two tasks.

However, the manipulation of the instruction had a different impact on the response order: in trials with the longest SOAs, the number of response reversals was higher in the condition with "free-choice" instruction than in the condition with "order" instruction. In more detail, in Experiment 1 (Hendrich et al., submitted) I found such a difference for SOA -400 ms, $t(24.520) = -3.657$, $p < .01$ (corrected for unequal variances), SOA -120 ms, $t(38) = -2.820$, $p < .01$, SOA 400 ms, $t(20.636) = 3.857$, $p < .01$ (corrected for unequal variances), and a nearly significant difference at SOA 120 ms, $t(38) = 1.801$, $p < .10$.

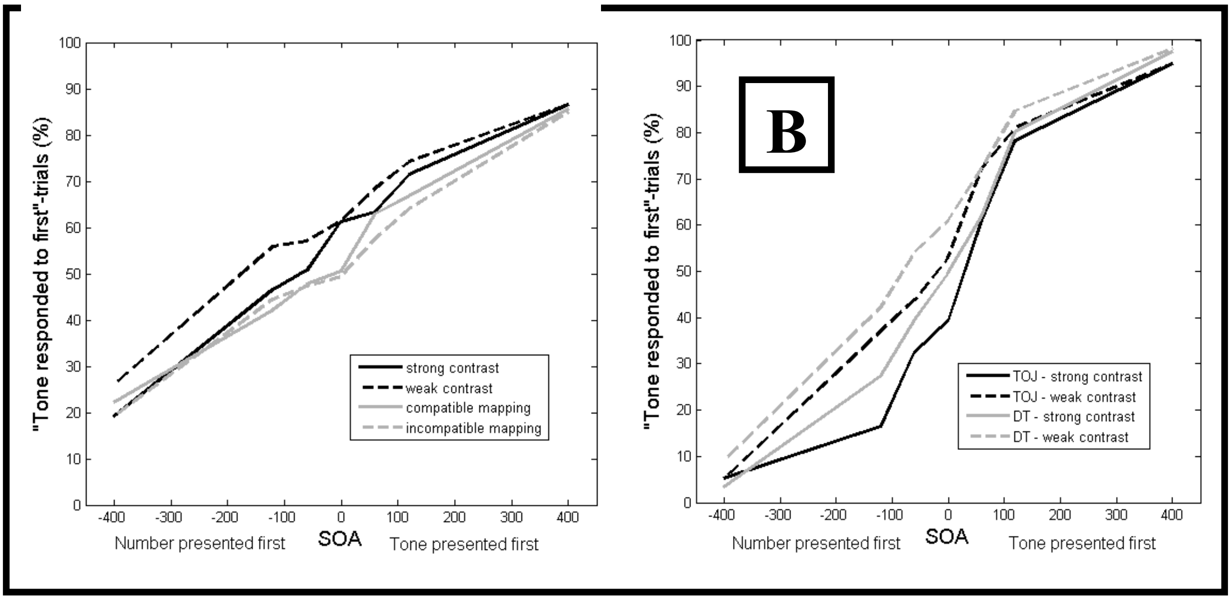

Figure 2. Proportion of trials in which the auditory task was responded to first for each SOA. Panel A. Effect of the instruction on response order if the participants are told to respond in the order of their choice (Hendrich et al., submitted). The graph shows that the prolongation of the visual perception stage (weak-contrast condition) leads to an increase of response reversals in trials in which the visual number task is presented first. The prolongation of the response selection stage (by using incompatible stimulus-response mapping instead of compatible mapping) has no effect on the response order. Panel B shows the effect of task requirements on the processing order (Hendrich et al., 2012). The proportion of trials in which the auditory tone task is responded to first increases if the participants have to perform a temporal order decision with an additional choice RT task (dual task [DT] condition) compared to a temporal order judgment (TOJ) task only. The influence of the task requirements seems to be dependent on the additional manipulations of the processing staged which were used in the experiments.

In Experiment 2 (Hendrich et al., submitted), I found the same result for SOA -400 ms, $t(19.67) = -3.139$, $p < .01$ (corrected for unequal variances), SOA 120 ms, $t(37) = 3.778$, $p < .01$; and SOA 400 ms, $t(17.72) = 4.235$, $p < .01$ (corrected for unequal variances). The results in Hendrich et al. (in preparation) were similar.

Additionally, the instruction had a significant effect on overall RTs, which were longer in the condition with “order” instruction than in the condition with “free-choice” instruction. For instance, in Experiment 1 (Hendrich et al., submitted) RT1 (number) showed this effect, $F(1, 35) = 5.724$, $p < .05$. Both results indicate that additional cognitive control processes were active in the condition with "order" instruction, in which the participants were told to respond in the order of stimulus presentation.

The results are in line with studies by Szameitat et al. (2006) and Sigman and Dehaene (2006), which assume that cognitive control is activated in dual-task studies with random task order. Most noticeably, Szameitat et al. (2006) split up "same-order" trials (trials which followed a trial with the same stimulus order) and "different-order" trials (trials in which the stimulus order had changed compared to the trial before). The authors found that "different-order" trials led to stronger activation in parts of the lateral prefrontal cortex (LPFC) compared to "same-order" trials. Szameitat et al. concluded therefore that the temporal coordination of two tasks is a function of the LPFC.

4. On the influence of task requirements on processing order and on the localization of the task order decision in the dual-task processing architecture

In the third study, Hendrich et al. (2012), I investigated two questions: the first question was whether task requirements have an influence on the processing order at the bottleneck Additionally, the manipulations I used in this study allowed to localize the point in time during processing at which the decision about the temporal order of the two tasks is made.

There are many studies on how temporal order decisions can be influenced by stimuli characteristics like, e.g., stimulus intensity (Hendrich et al., submitted, in preparation). What has to my knowledge not been investigated so far, is whether particular task requirements have an influence on temporal order judgments (TOJ; Hendrich et al., 2012).

However, there are studies which show that there is link between action planning and perception (e.g., Deubel & Schneider, 1996; Deubel et al., 1998; Witt & Proffitt, 2008).

Deubel and Schneider, for instance, could show that action planning requirements influence early perceptual processes. In their study, they asked participants to plan a saccade to a specific location. In addition, participants were asked to discriminate between the symbols “E” and “mirror-E”, either at the target location of the saccade or at an adjacent location. The participants performed best in stimulus discrimination if the two tasks (planning a saccade and the discrimination task) involved the same stimulus at a single location.

If action planning requirements influence early perceptual processes, e.g., by directing attention to the processed stimuli, then this may have an additional effect on the processing speed of the perceptual stimuli and thereby on temporal order decisions. One possibility to investigate this question, is to compare a regular TOJ task with a dual-task as the one I have used in my other experiments (Hendrich et al., submitted, in preparation). In other words, an auditory-visual TOJ task is compared with an auditory-visual dual task with random task order, in which the participants have to make a decision about the temporal order of the stimuli and additionally have to do choice RT tasks on the two stimuli.

There are few studies which have compared TOJ with dual tasks. One of those few is De Jong (1995), who used the TOJ task as a control condition for a dual-task paradigm with random task order. With this control condition, he wanted to ensure that the participants were able to correctly identify the order of stimulus presentation. His results showed, that the number of response reversals (i.e., trials in which the participants did not respond in the order of task presentation) was higher in the dual-task conditions than in the TOJ condition. Despite this result, he thought it unlikely that this difference in the number of response reversals was caused by the additional requirement to carry out a choice RT task in the dual-task condition. His assumption was based on findings by Sternberg et al. (1971). However, Sternberg et al. (1971), who presented an auditory and a cutaneous stimulus, asked their participants to pull a lever in response to a cue before one of the two stimuli and then, in a second step, judge the order of the stimuli by pressing a corresponding button. Hence, the paradigm used by Sternberg et al. (1971) put quite different requirements on the participants than the tasks used in De Jong (1995). Therefore, in my opinion the question whether an additional choice RT task has an influence in TOJ needed to be investigated more closely.

I investigated this question by comparing a visual-auditory dual task as used in Hendrich et al. (submitted, in preparation) with a TOJ task. As described above, in the dual-task condition the participants had to do a choice RT task and respond to the stimuli in the order of their presentation. In the TOJ condition, the same stimuli were shown as in the dual-task condition (one of three numbers and one of three tones) and the participants were asked to press two keys (one for the visual and one for the auditory stimulus) in the order of the stimulus presentation. In this context, the dual-task condition can be seen as a TOJ task with the added requirement to carry out a discriminative response on the processed visual and auditory stimuli. In order to avoid that the participants put attention to the identity of the stimuli in the TOJ condition, this condition was always presented before the dual-task condition and it was not mentioned in the instruction for the TOJ condition that a dual-task condition would follow in which the identity of the stimuli would have to be recognized.

A second question which could be investigated in the context of this study is, when during task processing the decision about the temporal order of the two stimuli is made. Task processing, as already noted, is roughly divided into three consecutive stages (Sanders, 1980, 1990; Sternberg, 1969): perception, response selection, and response execution. At some point of time during the processing of the two tasks, the judgment about their temporal order has to take place. Sigman and Dehaene (2006) developed a model of task processing, in which the task order is decided after the perceptual processes of the first presented stimulus. As already explained above, it is not clear whether the manipulations which Sigman and Dehaene (2006) used in their experiment for the manipulation of the perception and the response selection stage, really targeted the intended processing stages. Therefore, I aimed to investigate the question of the time of the temporal order decision in a more direct way by using the manipulations from Hendrich et al. (submitted), which I consider to be more appropriate for manipulating the processing stages of perception (Experiment 1, Hendrich et al., 2012) and response selection (Experiment 2, Hendrich et al., 2012) of the visual task. In the TOJ condition, only the perception stage was manipulated, as there is no response-selection stage which can be manipulated in this task condition.

I expected that the manipulations should lead to one of three possible outcomes for the DT condition: if the decision about the temporal order of the two stimuli is made at the very beginning of task processing, then the manipulation of the visual perception stage and the manipulation of the visual response-selection stage should not have an influence on response order. If the order judgment takes place after the perception stage, but before the response-selection stage, then only the manipulation of the perception stage should have an effect on response order (Hendrich et al., 2012). In case the decision about the temporal order is made after the response-selection stage, then both manipulations should have an effect on response order. The hypotheses are based on the assumption that manipulations can only affect the temporal order decision if the decision is made after the manipulated processing stage.

The hypotheses for the TOJ condition are similar: if the decision about the temporal order is made before or at the beginning of the perceptual processing, then the manipulation of the perception stage should not have an effect on response order. If the decision is made after the perception stage, then the manipulation of said stage should influence the response order.

Results & Discussion

Experiment 1 (Hendrich et al., 2012), in which the perception stage of the visual task was additionally manipulated, shows that the addition of choice RT tasks in the dual-task condition has an effect on temporal order decisions (see Figure 3, Panel B). An ANOVA with task condition (TOJ vs. DT), contrast condition (strong vs. weak contrast), and SOA (-400 ms, -120 ms, -60 ms, 0 ms, 60 ms, 120 ms, 400 ms) as within-subject factors revealed that the participants responded to the auditory task first more often in the DT condition than in the TOJ condition. This was reflected in a significant difference between the task conditions (TOJ task vs. dual task), $F(1, 17) = 6.029$, $p < .05$. The interaction of task condition and SOA was also significant, $F(6, 102) = 2.276$, $p < .05$. Further *t*-tests showed that the number of "tone-responded-to-first" trials was higher in the dual-task condition than in the TOJ condition for SOA -120 ms, $t(17) = -2.184$, $p < .05$, SOA -60 ms, $t(17) = -2.130$, $p < .05$, and SOA 0 ms, $t(17) = -2.613$, $p < 0.05$. In trials with negative SOAs the visual number task was presented before the auditory task.

In Experiment 2, in which the response-selection stage of the visual task was manipulated, the results were similar. Here, the data was submitted to an ANOVA with task condition (TOJ compatible mapping vs. DT compatible mapping vs. DT incompatible mapping) and SOA as within-subject factors. The ANOVA did not show an overall effect of task condition, $F(1.195, 21.510) < 1$ (Greenhouse-Geisser corrected), but visual inspection of the data suggested a significant difference between the TOJ condition and the DT condition with compatible stimulus-response mapping for trials with negative SOAs (in which the visual number task is presented first). A statistical comparison between the two conditions confirmed the impression: if only the TOJ condition and the DT condition with compatible mapping were included in the analysis, the interaction of task condition and SOA was significant, $F(6, 108) = 2.343$, $p < .05$. One-tailed *t*-tests showed significant differences between the task conditions for SOA -400 ms, $t(18) = -1.767$, $p < .05$, SOA -60 ms, $t(18) = 1.868$, $p < .05$, and SOA 400 ms, $t(18) = 2.117$, $p < .05$. For SOA -400 ms, the participants responded to the auditory task first more often in TOJ condition, while the opposite was the case for SOAs -60 ms and 400 ms.

With the results of the experiments in Hendrich et al. (2012) I could show that the additional requirement to do a choice-RT task has an effect on temporal order decisions. However, this effect seems to be dependent on the manipulation of the processing stages in Experiment 1 and 2. In more detail, the participants in Experiment 1 responded to the auditory task first more often in the DT condition than in the TOJ condition, and this effect was especially prominent in trials in which the visual task was presented first. A possible explanation for this effect is that the perception stage of the visual task was manipulated. The participants might have already assessed the visual task as the more difficult one in the TOJ part of the experiment. In the subsequent dual-task part, the additional requirement to perform choice-RT tasks on the presented stimuli might have led them to prefer to respond to the auditory task first more often, as it was considered the easier one. In Experiment 2, the results were similar, albeit not as clear as in Experiment 1. As the visual task was also manipulated in this experiment, the explanation for the observed effect might be the same: the visual task was considered as the more difficult one and therefore the auditory task preponed in the response order.

Regarding the question of the point in time during task processing at which the decision about the temporal order of the two stimuli is made, I found the following results: In Experiment 1 (Hendrich et al., 2012), I found that the manipulation of the perception stage (strong vs. weak contrast of the visual stimulus), has an influence on response order in both task conditions (TOJ and DT), $F(1, 17) = 22.962$, $p < .01$. The participants responded to the auditory task first more often in the condition with weak contrast of the visual stimuli than in the condition with strong contrast. In Experiment 2 (Hendrich et al., 2012), I found no such effect of the manipulation of the visual response-selection stage in the DT condition. The results imply, that the decision about the temporal order of the two stimuli is made after the perceptual processing in both task conditions, TOJ tasks and DT. For the DT condition, the results additionally suggest that the decision is made before the response-selection stage, as the manipulation of the response-selection stage in the DT condition fails to have an effect on response order. The results support the findings by Sigman and Dehaene (2006).

General discussion

While there are many studies which support the idea of a central response-selection bottleneck (e.g., Pashler, 1994; Pashler & Johnston, 1989; Schubert, 2008), only few have investigated the question how the processing order at this bottleneck is determined. Factors that have been discussed in literature are the expectations of the participants (De Jong, 1995; Luria & Meiran, 2003), and the arrival time at the bottleneck (Sigman & Dehaene, 2006; Leonhard & Ulrich, 2011). The experiments in the described publications investigated several possible factors, arrival time at the bottleneck, instruction, and task requirements, and thereby gained new findings on the above mentioned question. In the following paragraphs I am going to summarize and discuss the findings.

Arrival time at the bottleneck

So far, there has been little research on whether the arrival time at the bottleneck is a determinant of the processing order at the central bottleneck. Additionally, the limited research that does exist, led to contradictory findings. The findings of Hendrich et al. (submitted) and Hendrich et al. (in preparation) provide support for the validity of the "first-come, first-served" principle. In other words, the task which enters the bottleneck first, is processed first. This could be shown by prolonging the perception stage and the response selection stage of the first presented task. The perception stage was manipulated in order to prohibit the earlier arrival of the first presented task at the bottleneck. This should lead to an increase in response reversals, i.e., the second presented task should arrive at the bottleneck earlier than the first presented task and therefore be responded to first. The manipulation of the response selection stage should not have an influence on the earlier arrival of the first presented task at the bottleneck and therefore not have an influence on the processing order. This could be shown by the experiments in Hendrich et al. (submitted).

In addition, the findings of Hendrich et al. (in preparation) show that the findings are not limited to the manipulation of the visual task, but could be extended to the manipulation of the auditory task. To my knowledge, this manipulation has not been done before and thus provides further support for the general validity of the “first-come, first-served” principle.

Instruction

According to the findings of Hendrich et al. (submitted) and Hendrich et al. (in preparation), another determinant of the central processing order seems to be the instruction given to the participants. While the manipulation of the instruction did not change the general effect of the arrival time at the bottleneck, it led to a small modification of the results. When the participants were told to respond in the order of stimulus presentation, the number of response reversals in trials with long SOAs (400 ms) decreased compared to when they were told to respond in the order of their choice. This finding supports the assumption that participants have (at least) some control over the response order. The finding can be reconciled with fMRI-studies which show that the prefrontal cortex is activated in situations in which the task order is random and therefore unknown to the participants (see e.g., Szameitat et al., 2006).

Task requirements

A third factor which was identified in Hendrich et al. (2012), are the requirements of the presented tasks. The results of Hendrich et al. (2012) show, that it makes a difference for the response order, whether the participants are only required to identify the order of presentation of two stimuli (TOJ condition) or whether they also have to do choice-RT tasks on the presented stimuli (DT condition). The question of TOJ under the condition of an additional choice requirement is of relevance because visual and auditory information often not only have to be noticed but also require an appropriate reaction from the observer in a laboratory context as well as in a real world environment. Interestingly, the effect of the task requirements seems to be linked to the manipulation of one of the tasks (the visual task). In the DT condition, the participants responded to the auditory task first more often than in the TOJ condition, especially in trials in which the visual task was presented first. As suggested above, this finding might be linked to the perceived difficulty of the visual task.

Point in time when the decision about the temporal order is made

In Hendrich et al. (2012), another important question was investigated. When is the point in time during processing at which the decision about the temporal order of two stimuli is made? The perception and the response-selection stage of the visual task were manipulated in the DT condition, while in the TOJ condition it was only possible to manipulate the perception stage. The findings show, that in both task conditions, the decision is made after the perception stage, as its manipulation has an effect on the response order which should not be the case if the decision about temporal order was made before the perception stage. Additionally, in the DT condition, the manipulation of the response-selection stage did not influence response order, which implies that the decision about task order in the DT condition is made after the perception stage, but before the response-selection stage.

Outlook for future experiments

As the present work shows that the determination of task order at the bottleneck is not determined by a single factor but rather by many. There are of course other factors which could also be investigated with the described dual-task paradigm. Thus, in my view a next step is to identify further factors which play a role in determining task order in dual-task situations.

One possible candidate is emotion. Do emotions have an effect on task preference and do they thereby affect the task order? For example, there have been contradictory findings on whether there is a “positivity bias” (e.g., participants remember stimuli with positive emotional valence better than ones with negative valence; Grühn & Scheibe, 2008; Mather, Carstensen, 2005) or a “negativity bias” (negatively evaluated stimuli have a greater impact on participants than equally intense positive stimuli; Peeters & Czapinski, 1990; Huang & Luo, 2006; Ito, Larsen, Smith, & Cacioppo, 1998). This question could be investigated by using stimuli of positive and/ or negative emotional valence in a dual-task context and asking the participants to respond in the order of their choice.

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